Age Chronosequence Effects on Restoration Quality of Reclaimed Coal Mine Soils in Mississippi Agroecosystems

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Abstract: Surface mining drastically disturbs landscapes and soil properties. Reclamation can restore and improve soil quality and biomass productivity. Time required for soil reclamation to restore soil quality to premined conditions in southeastern United States is unclear. The objective of this study was to evaluate chronosequence effects on restoration quality indicators in reclaimed coal mine soil from different land use landscapes and agroecosystems in Mississippi. Study sites in 0- to 3-, 5- to 7-, and 10- to 12-year-old reclaimed soils were compared with adjacent undisturbed sites. Soil samples collected at the 0- to 15-cm and the 15- to 30-cm depths within a grid in a radius of 3 m were mixed to produce composite samples and kept frozen until analyzed. Soil bulk density (ρb) was the highest (1.48 g cm^{-3}) in the youngest (<1 year) site and decreased with increasing age to the oldest (12-year) site (1.07 g cm^{-3}). Soil quality indicators (aggregate stability, total C, organic C, and microbial biomass C) increased with increasing reclamation age in forest and grass ecosystems. Concentrations of C were greater at the summit than at shoulder and foot-slope positions. Soil pH, Ca, Mg, Cu, and Zn were higher in newly reclaimed soil than in soils reclaimed 12 years earlier possibly because of reclamation liming practices, which buffer pH to greater than 7.0 in newly reclaimed sites. Reclamation practices improved soil quality over time. Soil quality indicators reached levels similar to those of undisturbed soil within 7 to 12 years after reclamation, indicating successful reestablishment of healthy and sustainable soils in the postmining ecosystems.

Key Words: Land use, landscape, summit, shoulder, chronosequence, coal mine.

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Surface mining causes drastic disturbances to the soil profile and alters soil physical and structural properties (Shukla et al., 2004a; Korcak, 1995). Several decades of research have shown that surface coal mining negatively impacts soil physical, chemical, and biological properties and results in the breaking of soil aggregates and exposure of the C fraction to microbial breakdown (Six et al., 2000). One of the most consistent impacts of disturbance associated with surface coal mining is loss of soil organic matter (SOM), including organic carbon (OC), which is the major indicator of soil quality (Severson and Gough, 1983; Harris et al., 1993; Akala and Lal, 2001; Shukla et al., 2004a). Surface coal mining decreases both soil OC (SOC) and nitrogen (N) pools, disturbs soil structure, and reduces biomass productivity (Shrestha and Lal, 2010). Reclamation of disturbed coal mine soils has the potential to improve soil quality and biomass productivity over time (Lal et al., 1998; Shukla et al., 2004b). The ultimate goal of mine land reclamation and revegetation is reestablishment of a productive, healthy, and sustainable ecosystem suitable for postmining land use (Harris et al., 1996). The time required for an effective soil reclamation process in the southeastern United States to restore soil quality to premined conditions is unclear. At the pedon scale, variability of some soil properties tends to be greater in reclaimed soils, whereas variability of other soil properties is similar to that of undisturbed soils; at the landscape scale, variability of reclaimed soils is less than that of undisturbed soils for most parameters (Bearden, et al., 2003).

Assessing the C sequestration potential of reclaimed mine soils is important for preserving environmental quality and ecosystem sustainability. Sequestered carbon and increased organic matter and other nutrients have important roles that impact quality characteristics of reclaimed coal mine soil in disturbed soils during reclamation (Thomas et al., 2001). To understand the sustainability and functionality of an agroecosystem in a reclaimed coal mine soil, it is important to characterize these quality indicators and to understand how these indicators change and improve with years after reclamation. Several studies have reported the effects of reclamation on improvement of soil physical, chemical, and biological properties over time (Akala and Lal, 2001; Carter and Ungar, 2002; Juwarkar et al., 2010; Keskin and Makineci, 2009; Nyamadzawo et al., 2008; Shrestha and Lal, 2007, 2008; Shukla et al., 2005; Ussiri et al., 2006a, 2006b). For example, the results of a chronosequence study of reclaimed coal mine soils ranging from 5 to 25 years indicated that soil N, P, and organic C increased with time (Boerner et al., 1998). The organic matter content of a soil at the 0- to 20-cm depth 13 years after reclamation was about 2.5-, 2.0-, and 3.1-fold higher than that of 1-, 3-, and 4-year-old soils, respectively (Zhongqiu et al., 2013). Another study also showed that C and N pools and bulk densities were strongly related with reclamation age and the rates of ecosystem C and N sequestration peaked after 10 to 15 years of reclamation; thereafter, the rate of sequestration decreased as reclamation age increased (Shrestha and Lal, 2010). Wick et al. (2009) reported that reclaimed soils recovered structurally toward a native soil condition after 10 to 15 years of reclamation. In a chronosequence study of five reclaimed coal mine soils ranging from 8 to 40 years after reclamation, Sourkova et al. (2005b) reported that vegetation type and postreclamation land use have greater and more important roles in soil quality improvement than the soil substrate quality. Shrestha and Lal (2007) observed that C and N pools were restored faster in reclaimed coal mine soils under grass (pasture/hay) than under forest land use. The rates of C sequestration, microbial activity, and nutrient cycling depended on biomass productivity of the plant ecosystems established on reclaimed sites and on the soil quality. Vogel (1987) reported that microbial communities and their associated C storage and nutrient cycling capacities could be accelerated and restored to predisturbance levels in reclaimed ecosystems. Merrill et al. (1998) reported that physicochemical

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characteristics and biological properties of reclaimed soils were strongly influenced by climate and ecosystem, time after reclamation, and land management. Soil quality is composed of many interrelated factors, which must be investigated to determine how they are influenced by reclamation age, reclamation practices, and land use. The effects of reclamation age on quality characteristics and the potential benefits of increased C sequestration in reclaimed mine soils have been reported mainly in temperate and cold climatic conditions (Rumpel et al., 1999; Akala and Lal, 2000;Gast et al., 2001; Stahl et al., 2003; Maharaj et al., 2007). The effect of reclamation age on soil development in the high-precipitation, humid, subtropical climate of Mississippi in southeastern United States has not been investigated. Therefore, the objective of this study was to evaluate soil physical, chemical, and biological properties of different age soils in reclaimed mine sites under different land uses and landscape positions.

MATERIALS AND METHODS

Study Site Characteristics

The study was conducted on reclaimed soils at a surface coal mine (Red Hills Mine) in east central Mississippi at approximately 33.3 N latitude and 89 W longitude. A sequence of different reclamation age soils was established to evaluate physical, chemical, and biological properties of reclaimed soils. Soil sites were chosen with similar characteristics, such as slope and landscape position. Three replicate sites of each soil age, including 0 to 2, 5 to 7, and 8 to 12 years after reclamation, and undisturbed (control) soils were selected (Fig. 1). All reclaimed sites had been reclaimed by the coal mining company and had received similar reclamation treatments. After regulatory approval of suitability demonstrations required by state and federal laws, oxidized

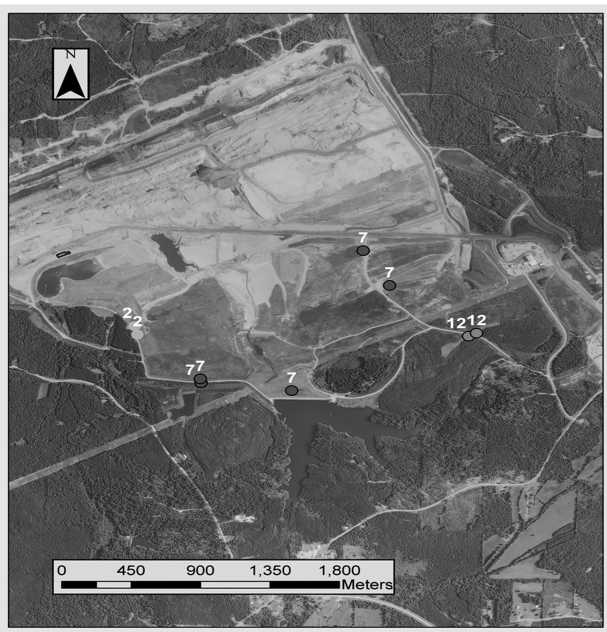

FIG. 1. Coal mine aerial photograph showing colored dots marking locations of study sites where soil samples were taken. Numbers indicate reclamation ages in years. Dot represent 12 years, 7 years, and 2 years after reclamation.

overburden materials were used as topsoil and/or subsoil substitutes during reclamation. During reclamation, the sites were fertilized with conventional inorganic fertilizer and seeded with grass. In the second year of reclamation, most sites were planted to loblolly pine, per original land owner requests. Undisturbed sites were a natural mixture of native deciduous trees and understory species. The area has general upland hills topography with a maximum elevation of 161 m (529 ft) and a subtropical humid climate with an annual rainfall (30-year mean) of 1,373 mm (54 in). The predominant land use in the area is agriculture and forestry. The predominant surface soil texture before mining was silt loam with a B horizon of 35 to 55% clay. Oxidized overburden materials are used as a substitute for both topsoil and subsoil in nonprime farmland reclamation. For prime farmland reclamation, oxidized overburden materials are used as a substitute for subsoil, then covered by replaced native topsoil. The reclaimed lands are predominantly prepared for use as pastures and forests and for recreation. The sites in the study were surface mined for coal and reclaimed. The reclaimed soils at the Red Hills Mine have been tentatively classified as fine-loamy, siliceous, active, nonacid, thermic Alfic Udarents, and the proposed Red Hills Series is currently under review for use in National Cooperative Soil Survey product delivery (E. F. Janak, Jr., CPSS, personal communications, 2013).

Soil Sampling and Analysis

Bulk and individual core soil samples were collected from the selected sites at reclaimed ages of 12, 7, and 2 years in both forest and grass ecosystems. Samples were also taken from a recently reclaimed site (age, 0 year). Bulk and soil core samples from adjacent nonmined forest (control) sites were collected for use as references in comparisons of soil development at reclaimed sites. In the forest ecosystem, all sites were hilly, so soil samples were collected at the 0- to 15-cm and the 15- to 30-cm depths from three landscape positions, the summit, the shoulder, and the foot-slope, in each site to examine landscape position effect on reclaimed soil properties. In contrast, the grass cover ecosystem site was level, so grass cover ecosystem soil samples represented one landscape position. Soil samples were taken from three different (replicate) sites in each land use ecosystem. Additional core samples for ρb analysis were taken from summit positions at each reclamation age site. Slopes at test sites ranged from 0 to 10%. Five cores, taken from 0- to 15-cm and 15- to 30-cm depths within a grid radius of 3 m (10 ft) at each site and position, were mixed thoroughly to comprise a single composite sample per grid, and three replicate composite grid samples were collected at each site. Soil samples were sealed in plastic bags and transported to the laboratory in a cooler and held at 4°C until analyzed. The double-ring soil sample procedure was used to collect samples for soil ρb determination (Blake and Hartge, 1986).

Soil aggregate stability was determined from bulk soil samples collected by shovel excavation from 0- to 15-cm depth. Soil aggregate stability was determined on 2 g of air-dried soil by the method of Kember and Rosenau (1986). Briefly, soil was added to a 250-μm sieve and repeatedly submerged in 50 to 80 mL of distilled water 10 times min^{-1} for 5 min to disrupt the aggregate and to filter and collect the disintegration products. Materials remaining on the screen include coarse organic materials and sand particles greater than 250 μm. Smaller soil particles that passed through the sieve were dried in an oven at 105°C to determine the stable aggregate fraction {% = [stable aggregate/(stable + unstable aggregate)] × 100}.

Soil ρb was determined as described by Grossman and Reinsch (2002). A typical, double-cylinder, hammer-driven core sampler was used for obtaining soil samples for ρb. A 15-cm ring was placed inside the sampler and inserted by force into the top 0- to 15-cm depth, and the whole core was taken. Samples were weighed and oven-dried at 105°C and weighed again to get a constant weight (Ws). The volume of soil was assumed to be equivalent to the volume of the sample collection ring. Soil ρb was calculated by dividing the mass of soil by the volume (ρb = Ws/Vs), where Ws = weight of dry soil (g) and Vs = soil volume (cm^3). Total soil porosity was calculated from values of ρb and particle density (Dp) using the formula [1 - ρb/Dp] (Danielson and Sutherland, 1986).

Soil core samples were divided into two parts: one part was air dried for chemical analysis, including pH, EC, TC, TN, SOC, P, Ca, Mg, Cu, and Zn; the other part was kept moist and stored at 4°C for microbial biomass C (MBC) analysis. Coal C was determined by the chemo-thermo method (Ussiri and Lal, 2008), as reported by Lal (2008), and TC was measured using a dry combustion method and C/N analyzer (Elementar, GmbH, Hanau, Germany). About 2 g of the soil was used for the determination of total carbon (TC) and total nitrogen (TN) concentrations by the dry combustion method. Microbial biomass C was determined using microwave irradiation (Islam and Weil, 1998).

Soil organic C (carbonate) was measured by subtracting soil carbonate free C concentration from coal C. Soil inorganic C was determined by the modified method of Bundy and Bremner (1972). Two grams of soil were placed in a serum bottle and crimp-sealed. A glass syringe was used to inject 4 mL of 2 *M* HCl into the bottle for carbonate dissolution and removal as CO_2 gas. The CO_2 evolved was injected into a gas chromatograph (Shimadzu GC-14A) equipped with a thermal conductivity detector for CO_2 analysis. The volume of CO_2 evolved was converted to soil inorganic C concentration. Coal C was determined by the chemo-thermo method (Ussiri and Lal, 2008). Briefly, a finely ground 2-g soil sample was treated successively with 1 *M* HCl, 0.5 *M* NaOH, 10% HF, and 60% HNO_3 and then combusted in a muffle furnace at 340°C for 3 h. The remaining C fraction resistant to chemical extraction and thermal oxidation was taken as coal C, which was analyzed with a C/N analyzer. The soil organic C concentrations were obtained by subtracting the soil inorganic C and coal C concentrations from the TC concentration. Soil pH was measured electrometrically in a 1:2 (soil mass/water volume) mixture. Electrical conductivity (EC) was determined using a conductivity meter and air-dried soil at a soil mass/water volume ratio of 1:5 (Rhoades, 1996). Soil samples were also extracted using Mehlich 3 extractant (Mehlich, 1984) and analyzed for plant-available P using inductively coupled plasma spectrophotometry.

Aboveground Biomass Determination

A quadrate (1 × 1 m) was used for collecting the aboveground biomass from forest floor and pasture sites. To estimate the contribution of aboveground forest vegetation on mine soil in the forest ecosystem, forest litter was collected from three landscape positions (summit, shoulder, and foot-slope). Three quadrates were set (under the tree crown, canopy edge) for each landscape position. Litter inside the quadrates (including woody dead fallen biomass, leaves, undergrowth) was collected in May and October at the same locations, and composite samples were prepared for each quadrate. In the grassland (pasture) ecosytem, aboveground biomass was collected from three 1 × 1–m quadrates in each reclamation age site. All biomass samples were dried in an oven at 65°C for 72 h and weighed to calculate the total dry weight (Mg ha^{-1}). Larger quadrates (4 × 4 m) were also marked in each forest ecosystem reclamation age site, and the number of trees were recorded from three quadrates each at summit, shoulder, and foot-slope positions. The diameter at (1.37 m) breast height (DBH) of each tree within each 16-m^2 quadrate was measured, and the mean value was recorded for each quadrate. The height of each tree within each 16-m^2 quadrate was measured using a clinometer, and the mean was recorded for each quadrate.

Data Analysis

All data were examined by an analysis of variance using SAS (version 9.2 for Windows XP-Pro; SAS Institute, Inc., Cary, NC) to assess the effects of land use, landscape positions, and reclamation age on restoration quality of reclaimed coal mine soils. Differences between means were tested using the least significant difference ([LSD] $P = 0.05$).

RESULTS AND DISCUSSION

Reclamation Age and Soil Physical Changes

Results of soil analyses indicated that the quality characteristics of reclaimed coal mine soils improved with increasing reclamation age for both forest and pasture ecosystems (Figs. 2–9). Under both forest and grass cover, soil physical properties, including ρb and aggregate stability, were determined only at the 0- to 15-cm depth and in only one landscape position (summit), whereas chemical and biological properties were determined at 0 to 15 cm and 15 to 30 cm in all three landscape positions. Under forest and grass cover at the 0- to 15-cm depth, ρb 2 years after reclamation increased by 28 and 17%, respectively, compared with adjacent nonmined soils (Fig. 2). In reclaimed mine soils, ρb was highest in reclamation age zero sites (1.52 g cm^{-3}) and decreased with increasing reclamation age to 1.07 g cm^{-3} in reclamation age 12 sites. Averaged across reclamation ages, ρb under grass cover (1.48 g cm^{-3}) was greater than under forest ecosystem (1.42 g cm^{-3}) possibly because of the trampling effect of grazing

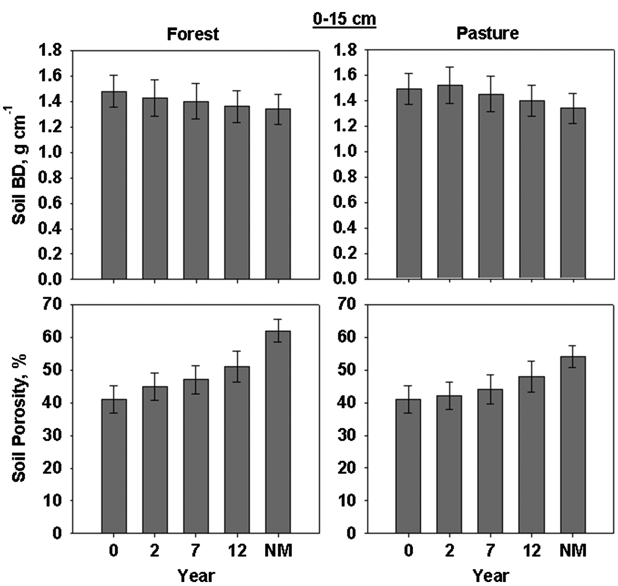

FIG. 2. Effects of reclamation age on soil bulk density and porosity at the 0- to 15-cm depth for both forest and grass (pasture) ecosystems in a reclaimed coal mine site.

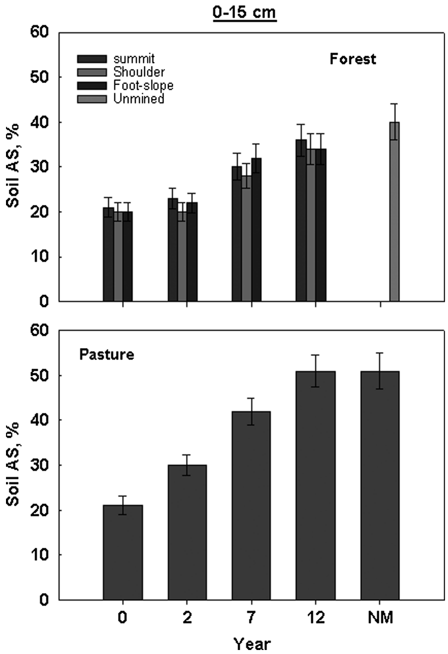

FIG. 3. Effects of reclamation age and landscape positions on soil aggregate stability at the 0- to 15-cm depth for both forest and grass (pasture) ecosystems in a reclaimed coal mine site.

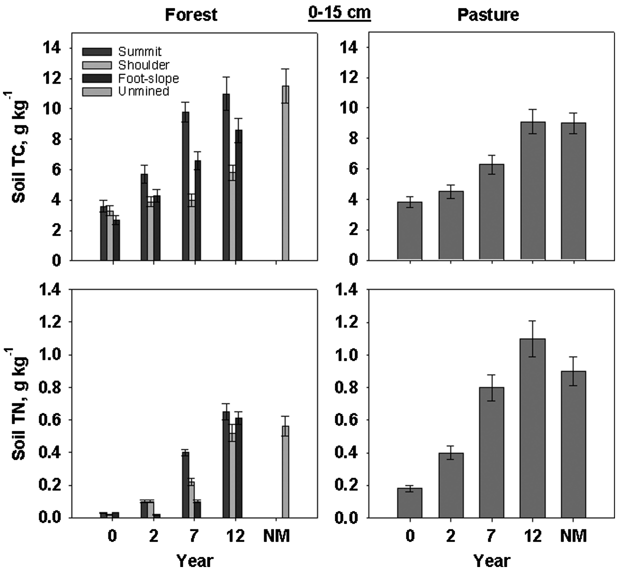

FIG. 5. Effects of reclamation age and landscape positions on soil total C and N at the 0- to 15-cm depth for both forest and grass (pasture) ecosystems in a reclaimed coal mine site.

animals (Shrestha and Lal, 2008). In agreement with our results, Sencindiver and Ammons (2000) also reported higher ρb in reclaimed soils compared with those at undisturbed sites. In contrast, Ganjegunte et al. (2009, 1982) reported no significant changes in ρb in the top 30 cm of reclaimed mine soil (<1 year after reclamation) compared with an undisturbed soil. The increase in ρb observed in our study in the age zero site is likely caused by soil compaction from heavy equipment used during reclamation, as also reported by Indorante et al. (1992). In contrast to soil ρb, soil porosity in both land use ecosystems increased with increasing reclamation age (Fig. 2). Nonmined soil in the forest ecosystem had the highest soil porosity.

Comparison of means from analysis of variance showed that, in general, soil aggregate stability increased with increasing reclamation age for all landscape positions in both forest and pasture ecosystems. Under forest vegetation, no differences in aggregate stability were observed among the landscape positions ($P < 0.05$). Averaged across landscape positions, the water-stable aggregate was significantly higher for reclamation age 12 sites (35%) than for age 7 (30%) age 3 (22%) sites. The magnitudes of aggregate

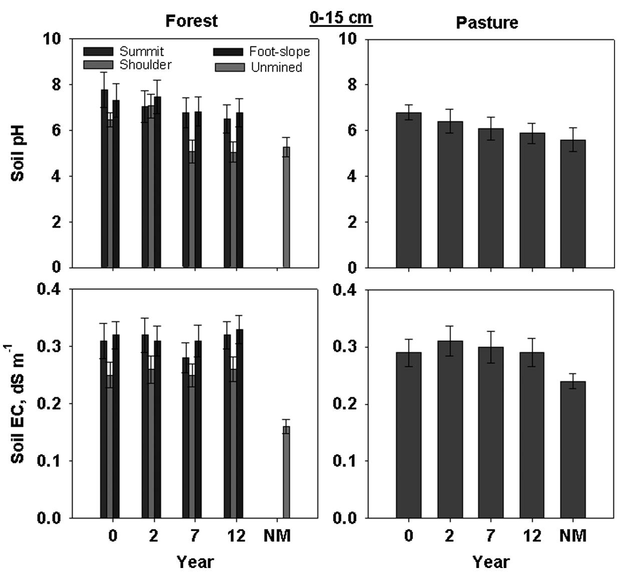

FIG. 4. Effects of reclamation age and landscape positions land use on soil pH and EC at the 0- to 15-cm depth for both forest and grass (pasture) ecosystems in a reclaimed coal mine site.

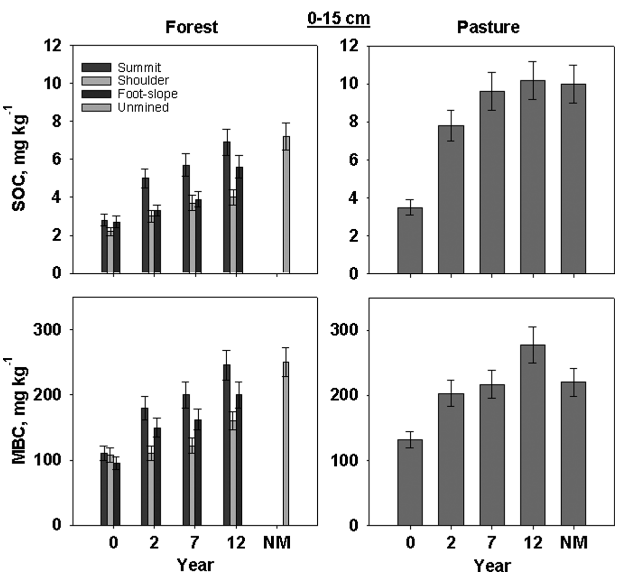

FIG. 6. Effects of reclamation age and landscape positions on soil organic C and microbial biomass C at the 0- to 15-cm depth for both forest and grass (pasture) ecosystems in a reclaimed coal mine site.

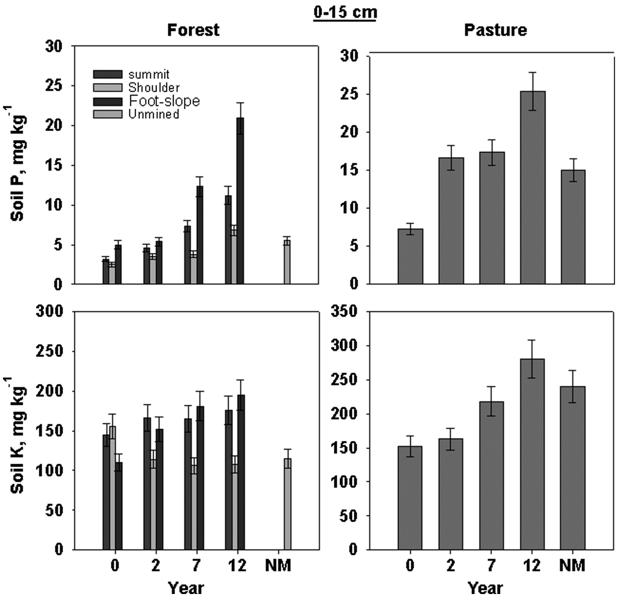

FIG. 7. Effects of reclamation age and landscape positions on soil P and K at the 0- to 15-cm depth for both forest and grass (pasture) ecosystems in a reclaimed coal mine site.

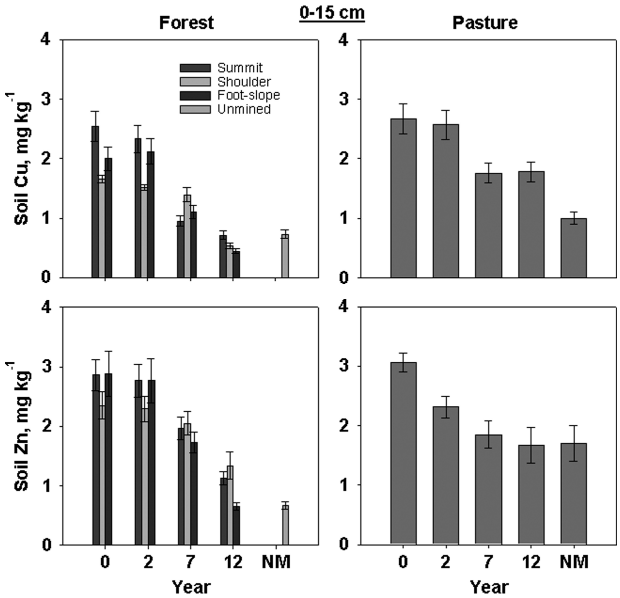

FIG. 9. Effects of reclamation age and landscape positions on soil Cu and Zn at the 0- to 15-cm depth for both forest and grass (pasture) ecosystems in a reclaimed coal mine site.

stability mean values for reclamation ages 12, 7, and 3 were, respectively, greater in the pasture (51, 42, and 30%) than in the forest ecosystem (35, 30, and 22%). Better aggregation or greater stability of aggregate under pasture than forest may be caused by higher amounts of C and a denser root system near the soil surface (Shrestha and Lal, 2007). A dense sodlike root system in the 0- to 5-cm depth in reclamation age 12 soil of the pasture/hay ecosystem most likely enhanced formation of stable microaggregates, which then coalesced to form macroaggregates, producing relatively more stable soil structure, with increased water infiltration capacity, decreased surface runoff potential, and improved soil water reserve capacity (Shaver et al., 2002). Averaged across landscape positions, the magnitudes of soil aggregate stability in reclamation age 12 sites were similar to those in nonmined soils under both forest and continuous pasture ecosystems (Fig. 3). These observations indicate the positive effect of reclamation on aggregate stability.

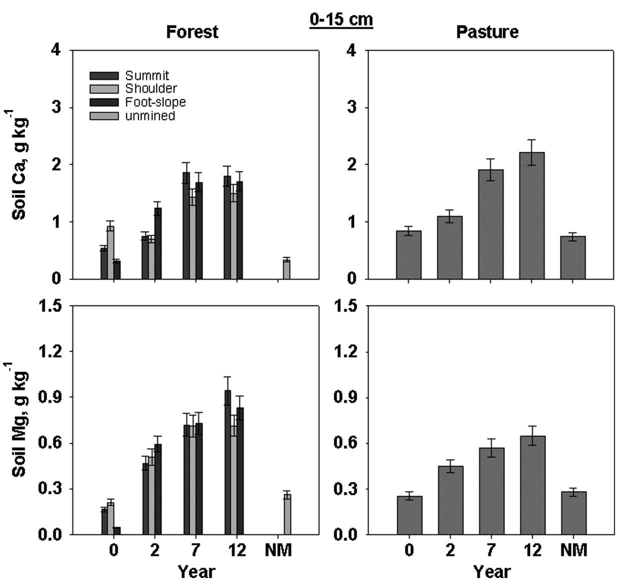

FIG. 8. Effects of reclamation age and landscape positions on soil Ca and Mg at the 0- to 15-cm depth for both forest and grass (pasture) ecosystems in a reclaimed coal mine site.

Reclamation Age and Soil Chemical Changes

Soil chemical properties, including pH, EC, and C, N, Ca, Mg, and micronutrient concentrations, were influenced by reclamation age and improved over time (Figs. 4–9). Soil EC was similar across site age in both forest and grass sites, and no differences in soil EC and pH were observed among landscape positions (Fig. 4). Soil pH is an important measurement for restoration of reclaimed mine soils because pH moderates availability of plant nutrients (Shrestha and Lal, 2011). Averaged across landscape positions under forest vegetation, soil pH was higher in newly reclaimed soil (7.2) than reclamation age 12 sites (6.1) possibly caused by reclamation liming practices that would buffer the pH to more than 7.0 in recently reclaimed sites as also reported by Howard (1979). Soil pH decreased with increasing reclamation age (Fig. 4).

Similar to pH, no differences in soil EC were observed among landscape positions and reclamation ages (Fig. 4). Averaged across landscape positions and reclamation ages, EC values at the 0- to 15-cm depth in forest ecosystems (0.31 dS m^{-1}) were 52% higher than those of undisturbed sites (0.16 dS m^{-1}). Similar patterns in soil EC changes at the 15- to 30-cm depth were observed for reclamation age in forest and pasture ecosystems (Tables 1 and 2). The EC in the 0- to 15-cm depth ranged from 0.16 to 0.24 dS m^{-1} in nonmined sites and 0.33 to 0.31 dS m^{-1} in reclaimed sites. For forest and pasture ecosystems, the EC in the 0- to 15-cm depth ranged from 0.16 to 0.24 dS m^{-1} in nonmined sites and 0.33 to 0.31 dS m^{-1} in reclaimed coal mine sites. Although EC increased after reclamation, no negative salt effects were observed on grass or tree growth in reclaimed soils of any reclamation age. Ganjegunte et al. (2009, 2011) also observed an increase in EC for the 0- to 5-cm depth of reclaimed compared with undisturbed sites. Such increases have been

TABLE 1. Chemical and Biological Properties* of Different Reclamation Age Soils in a Forest Ecosystem at the Red Hills Mine in Mississippi

Age	pH	EC	TC	TN	P	K	Ca	Mg	SOC	MBC	Cu	Zn
years		dS m^{-1}	---------------------------g kg^{-1}	-------------------------------------					------------mg kg^{-1}-----------			
0	7.18	0.31	1.01	0.15	0.0022	0.090	1.78	0.88	1.7	61	1.08	2.60
2	7.08	0.30	1.70	0.15	0.0024	0.089	1.66	0.72	2.7	72	1.10	2.82
7	7.19	0.28	2.3	0.12	0.0036	0.087	0.89	0.52	3.2	81	1.16	1.86
12	6.20	0.30	4.7	0.21	0.0047	0.105	0.59	0.14	3.8	122	0.40	1.09
NM	5.28	0.16	3.2	0.31	0.0036	0.106	0.34	0.26	6.4	146	0.75	0.87

*Values for pH, EC, TC, P, K, Ca, Mg, SOC, MBC, Cu, and Zn are means at the 15- to 30-cm depth, averaged across landscape positions.
EC: electrical conductivity; MBC: microbial biomass C; NM: nonmined; SOC: soil organic carbon; TC: total carbon.

attributed to soil contamination with overburden materials containing $CaCO_3$ (Shrestha and Lal, 2010). Contamination with overburden can occur during excavation, stockpiling, and replacement operations (Juwarkar et al., 2010).

Soil TC and organic C increased with increasing reclamation age in both forest and pasture ecosystems (Figs. 5 and 6). Initially, however, for the forest cover, TC and organic C at the 0- to 15-cm depth were 3.8 and 2.3 g kg^{-1}, respectively, in newly reclaimed soil compared with 11.5 and 7.2 g kg^{-1}, respectively, in nonmined sites, indicating an initial loss of 67 and 79%, respectively, of original total and organic C. These very high initial reductions in TC and organic C resulted from drastic soil disturbances during mining and reclamation activities. These activities deplete soil organic matter , increase oxidation, dilute C through horizon mixing, accelerate erosion, and produce little or no C inputs (Stahl et al., 2003). Landscape position had significant effects on soil TC and organic C in each reclamation age, except for newly reclaimed sites. For example, 12 years after reclamation under forest cover, soil concentrations of TC and organic C were much greater, respectively, for the summit (11.5 g kg^{-1} and 7.2 mg kg^{-1}) than shoulder (5.8 g kg^{-1} and 4.0 mg kg^{-1}) or foot-slope (8.6 g kg^{-1} and 5.6 mg kg^{-1}) positions (Figs. 5 and 6). In reclamation age 12 soils, TC and organic C at the summit position reached levels (11.5 g kg^{-1} and 7.2 mg kg^{-1}, respectively) similar to those of nonmined soils, indicating positive effects of reclamation practices on landscape stability and restoration of soil quality. At the 15- to 30-cm depth, for each reclamation age, no significant differences in soil TC and organic C concentrations were observed among landscape positions (data not shown). When averaged across landscape positions, soil TC and organic C increased with increasing reclamation age (Table 1). Although soil TC and organic C followed similar patterns at the 0- to 15-cm and the 15- to 30-cm depths, their magnitudes at the 15- to 30-cm depth (4.7 g kg^{-1} and 3.6 mg kg^{-1}, respectively) were 58 and 48% lower than those at the 0- to 15-cm depth (11 g kg^{-1} and 6.9 mg kg^{-1}, respectively).

Similar to results in the forest ecosystem, soil TC and organic C at the 0- to 15-cm depth increased with increasing reclamation age in the grass ecosystem (Figs. 5 and 6). Total C and organic C at the 0- to 15-cm depth in newly reclaimed soil in the grass ecosystem were 3.8 g kg^{-1} and 3.5 mg kg^{-1}, respectively, or 62 and 60% of their respective values (10.0 g kg^{-1} and 9.0 mg kg^{-1}) in the nonmined soil, indicating a loss of C during mining and initial reclamation activities. Similar to forest ecosystems, soil total and organic C in reclaimed grass ecosystems 12 years after reclamation reached values similar to those in nonmined sites (Figs. 5 and 6), indicating the restoration of soil quality indicators over time. In soil comparisons of the same reclamation age and landscape positions at the 0- to 15-cm depth, soil organic C was 32% greater in the grass ecosystem than the forest ecosystem (10.2 vs. 6.9 mg kg^{-1}, respectively). The high soil organic C was expected in this ecosystem because it was consistently under cover of grass with intensive shallow root production and also received manure from grazing animals.

Microbial biomass C (MBC) content in reclaimed soils under both forest and grass cover followed a trend of increasing from a low level in newly reclaimed soils (104 and 132 mg kg^{-1}, respectively) to higher levels of MBC in reclamation age 12 soils (246 and 277 mg kg^{-1}, respectively). For the 0- to 15-cm depth, MBC levels were lowest in the newly reclaimed site, where they were reduced as a result of the process of soil removal before mining and replacement of approved topsoil and subsoil substitute materials after mining; however, MBC recovered at reclamation age 12 soils to concentrations equal to or greater than those in the native nonmined soils (Fig. 6). Regardless of vegetative cover,

TABLE 2. Chemical and Biological Properties* of Different Reclamation Age Soils in a Grass Ecosystem at the Red Hills Mine in Mississippi

Age	pH	EC	TC	TN	P	K	Ca	Mg	SOC	MBC	Cu	Zn
years		dS m^{-1}	---------------------------g kg^{-1}	-------------------------------------					------------mg kg^{-1}-----------			
0	7.2	0.32	1.08	0.04	0.0026	0.075	1.8	1.50	2.4	91	2.65	1.81
2	6.4	0.31	2.61	0.08	0.0035	0.086	1.9	1.48	2.6	101	2.88	1.72
7	6.1	0.30	2.74	0.10	0.0078	0.101	0.84	0.45	2.3	108	0.99	1.26
12	5.9	0.29	3.0	0.09	0.0096	0.108	1.10	0.26	3.3	133	0.98	0.95
NM	6.1	0.15	3.5	0.32	0.0021	0.96	0.21	0.11	2.4	92	0.88	0.91

*Values for pH, EC, TC, P, K, Ca, Mg, SOC, MBC, Cu, and Zn are means at the 15- to 30-cm depth, averaged across landscape positions.
EC: electrical conductivity; MBC: microbial biomass carbon; NM: nonmined; SOC: soil organic carbon; TC: total carbon.

recovery of soil MBC was approximately doubled from an average of 118 mg kg^{-1} soil in the newly reclaimed soils to 221 mg kg^{-1} in the reclamation age 12 soils. Landscape position also had significant effects on MBC in all reclamation age soils. For example, soil MBC concentrations in reclamation age 12 soils under forest cover were much greater for the summit (246 mg kg^{-1}) than shoulder (160 mg kg^{-1}) or foot-slope (162 mg kg^{-1}) (Fig. 6). The magnitude of soil MBC followed the same pattern as soil organic C and increased with increasing reclamation age. Generally, there is a strong positive correlation between the amount of soil organic C and MBC (R^2 = 0.92) because soil organic matter is a principal energy source for soil microorganisms. Vogel (1987) reported that MBC was highly related to interaggregate particulate organic matter (available for microbial utilization; R^2 = 0.70, P = 0.01) and intra-aggregate particulate organic matter (protected by soil aggregates; R^2 = 0.81, P = 0.001), thus this tight link between soil organic matter and MBC indicates a "recovered" reclaimed ecosystem. Results in the present study are in agreement with the work by Banning et al. (2008), who reported that labile sources of carbon inputs, such as organic C, are used quickly by microbial communities, resulting in a rapid increase in MBC and recovery of disturbed ecosystems. In the present study, soil MBC in the grass ecosystem recovered to nonmined levels in 7 to 12 years, indicating recovery of the microbial community in the reclaimed soils.

Concentrations of TN in the reclaimed mine soils increased with increasing reclamation age and followed a trend similar to that of the soil organic C showing a significant decrease caused by mining and reclamation activities in newly reclaimed sites (Fig. 5). Soil TN concentrations for the forest cover at the 0- to 15-cm depth were 0.56 g kg^{-1} in the undisturbed soil and 0.03 g kg^{-1} in the newly reclaimed soil, indicating a 95% loss of original N from soil disturbance caused by mining and reclamation activities. In agreement with these results, Ganjegunte et al. (2009) reported N losses of 65.3% at the 0- to 5-cm depth and 58.0% at the 5- to 15-cm depth. Except for newly reclaimed soils, landscape position had significant effects on soil TN recovery in reclamation soils. The concentration of soil TN at the summit was greater than that at shoulder and foot-slope positions in reclamation age 3 and 7 soils. No differences in soil TN were observed among landscape positions in reclamation age 12 soils. The magnitude of TN averaged across landscape positions in reclamation age 12 soils was similar to that of nonmined soil (0.59 vs. 0.56 g kg^{-1}, respectively). In the grass ecosystem, soil TN increased with increasing reclamation age and, in a comparable landscape position, soil TN recovered faster than in the forest ecosystem. For example, soil TN at the 0- to 15-cm depth was 0.81 g kg^{-1} in reclamation age 7 soil compared with 0.9 g kg^{-1} in nonmined soil, but in the forest ecosystem, soil TN, averaged across landscape positions, was 0.59 g kg^{-1} in reclamation age 12 soil and 0.56 g kg^{-1} in nonmined soil (Fig. 5). At the 15- to 30-cm depth, no differences in soil TN were observed among reclamation ages; in forest and grass ecosystems, however, the magnitudes of TN were much smaller at the 15- to 30-cm depth (0.09 and 0.21 g kg^{-1}, respectively) than at the 0- to 15-cm depth (0.59 and 1.1 g kg^{-1}, respectively) (Fig. 5; Tables 1 and 2).

For the forest ecosystem, the concentrations of P and K in reclaimed coal mine soils at the 0- to 15-cm depth increased with increasing reclamation age (Fig. 7). The greatest P concentration was found in reclamation age 12-year soils (13 mg kg^{-1}) and the lowest in newly reclaimed soil (3.3 mg kg^{-1}). The concentration of P in reclaimed mine soils was also affected by landscape position, especially in reclamation age 12 soil, in which soil P content in the foot-slope position (20.9 mg kg^{-1}) was much greater than that at summit (11.2 mg kg^{-1}) and shoulder (6.8 mg kg^{-1}) positions (Fig. 7), indicating possible P redistribution by runoff into foot-slope positions. Phosphorus levels in reclaimed mine soils reached nonmined levels (5.5 mg kg^{-1}) in reclamation age 3 soil and exceeded premined levels in reclamation age 7 soil, especially in summit and foot-slope positions.

In the grass ecosystem, soil P concentrations followed a pattern similar to soil P in the forest ecosystem, increasing as reclamation age increased. Although soil P concentration for the grass ecosystem reached the premined level (15 mg kg^{-1}) by reclamation age, P concentrations for grass cover in all reclamation ages were greater than those in the forest ecosystem (Fig. 7). At the 15- to 30-cm depth for both forest and grass ecosystems, soil P concentration increased with increasing reclamation age and were about one half the levels found at the 0- to 15-cm depth (Tables 1 and 2).

Potassium levels at the 0- to 15-cm depth in the forest ecosystem were similar across reclamation ages from newly reclaimed to reclamation age 12 soils. No differences in K levels were observed between summit and foot-slope positions; however, the K levels in those positions were greater than K levels at the shoulder position (Fig. 7).

Averaged across landscape positions and reclamation age, the K level of reclaimed soil was 23% higher than that of nonmined soil (148 and 115 mg kg^{-1}, respectively). In the grass ecosystem, soil K level at the 0- to 15-cm depth increased with increasing reclamation age and exceeded the nonmined K level in reclamation age 12 soil (240 and 280 mg kg^{-1}, respectively). At the 15- to 30-cm soil depth, averaged across landscapes and reclamation age, soil K concentrations in forest and grass ecosystems were 37 and 54% less, respectively, than levels at the 0- to 15-cm depth (Fig. 7; Tables 1 and 2).

At the 0- to 15-cm depth in reclaimed soil, other nutrients, including Ca, Mg, Cu, and Zn, were influenced by reclamation age but not by landscape positions (Figs. 8 and 9), and their concentrations decreased with increasing reclamation age in both forest and grass ecosystems. Averaged across landscape positions under forest vegetation, soil Ca, Mg, Cu, and Zn concentrations were higher in newly reclaimed soil than in reclamation age 12 soil.

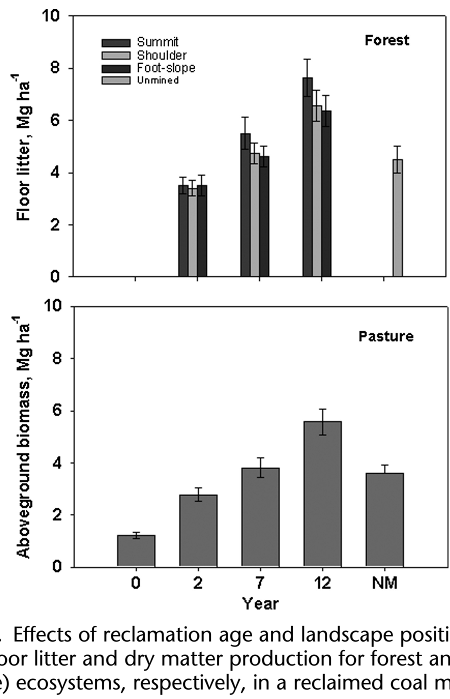

FIG. 10. Effects of reclamation age and landscape positions on forest floor litter and dry matter production for forest and grass (pasture) ecosystems, respectively, in a reclaimed coal mine site.

Under forest ecosystem, averaged across landscape positions, the concentrations of Ca and Mg in newly reclaimed soil (1.71 and 0.71 g kg^{-1}, respectively) were 80 and 63% greater than those in nonmined levels (0.34 and 0.26 g kg^{-1}), respectively (Fig. 8). The greater Ca and Mg concentrations in the newly reclaimed soils compared with those in nonmined soils could be related to the reclamation liming practices (Fig. 4). In the grass ecosystem, similar patterns were observed for soil Ca and Mg concentrations. At the 15- to 30-cm depth, in both forest and grass ecosystems, soil Ca and Mg levels were influenced by reclamation age, but concentrations were smaller than those in the 0- to 15-cm depth.

Similar to Ca and Mg, soil Cu and Zn decreased with increasing reclamation ages. Averaged across landscape positions, the concentrations of Cu and Zn in the newly reclaimed soil (2.06 and 2.70 mg kg^{-1}, respectively) were 56 and 75% greater than those in nonmined soil (0.73 and 0.67 mg kg^{-1}, respectively) (Fig. 9). In the grass ecosystem, a similar pattern was observed for soil Cu and Zn concentrations but with slight differences in their concentrations as compared with those in the forest site.

Forest Litter and Grass Biomass

The primary source of soil organic carbon in a reclaimed coal mine soil is plant litter, which is directly related to the production of plant biomass. Whereas belowground biomass (i.e., roots) is relatively difficult to estimate, aboveground litter and dry matter were measured for forest and grass covers, respectively. For both forest and grass ecosystems, floor litter and dry matter production increased with increasing reclamation age (Fig. 10). Litter masses on the forest floor and dry matter production from grass cover were greater by 35 and 45%, respectively, in reclaimed sites than those in nonmined sites by reclamation age 12 (Fig. 10). In the forest ecosystem, biomass accumulation in reclamation age 7 sites matched those in the nonmined (native) sites, whereas biomass production in the grass ecosystem did not match those in nonmined levels until reclamation age 12 (Table 3). Increased biomass production in the reclaimed soils in this study seems to be a critical part of the successional reclamation practice.

TABLE 3. Biomass Production by Soils of Different Reclamation Ages and Landscape Positions in Forest and Pasture Ecosystems at the Red Hills Mine in Mississippi

		Forest			Pasture
Reclamation Age	Landscape Position	DBH*	Height	Forest litter	DM
years		cm	m	Mg ha^{-1}	Mg ha^{-1}
2	Summit	7.3	3.5	3.51	2.78
	Shoulder	6.4	3.4	3.42	—
	Foot-slope	7.0	3.6	3.5	—
	Average	6.9	3.5	3.48	—
7	Summit	10.5	4.9	5.51	3.81
	Shoulder	8.1	3.9	4.75	—
	Foot-slope	9.2	4.5	4.62	—
	Average	9.3	4.5	4.96	—
12	Summit	18.6	7.3	7.63	5.57
	Shoulder	13.8	5.6	6.57	—
	Foot-slope	14.9	6.1	6.37	—
	Average	15.8	6.3	6.86	—
NM		27.8	11.2	4.52	3.62

*DBH mean per tree.

DBH: diameter at breast height; DM: dry matter; NM: nonmined.

CONCLUSIONS

The results of this preliminary study indicate that land reclamation age and ground cover establishment at the Red Hills Mine improved soil aggregate stability and enhanced soil C sequestration and nutrient cycling. The magnitudes of soil aggregate stability, TC, organic C, and MBC were greater at the summit compared with those at the shoulder and foot-slope positions; however, soil P level was greatest at the foot-slope position. The accumulation of MBC in soil seemed to increase with increasing reclamation age. Under Mississippi climatic conditions, reclamation coal mine practices improved major soil quality indicators, such as soil C and aggregate stability, which reached levels similar to those of nonmined soil in 7 to 12 years, indicating establishment of healthy and sustainable postmining ecosystems.

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